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METHOD AND APPARATUS FOR IMPROVED CATALYTIC CONVERTER PERFORMANCE

TECHNICAL FIELD

[0001] The present invention relates to an internal combustion engine. More specifically the present invention relates to a method and apparatus for improving the performance of a catalytic converter used to control emissions in an internal combustion engine.

BACKGROUND OF THE INVENTION

[0002] Increased regulation in the automotive industry has reduced the allowable levels of exhaust emissions such as hydrocarbons (HC), carbon monoxide (CO) and nitrogen oxides (NOx), generated by vehicles. Typically, automobiles use catalytic converters to achieve regulated exhaust emission levels.

[0003] The catalytic converter is attached to the exhaust of an internal combustion engine (ICE) to chemically purify the exhaust. Modern three-way catalytic converters comprise an Al2O3 monolithic walled substrate, which acts as a support. A mixture of Pt, Pd, Rh, CeO2, and other elements, compounds, and rare earths are deposited onto the substrate to form a catalytic surface with oxygen storage characteristics. When hot exhaust gases make contact with the coated surface of the converter, the catalytic surface promotes the oxidizing of engine exhaust HC and CO into CO2 and H2O; and the reduction of NOx (NO / NO2 /NO3, etc.) to N2. CeO2 in a converter promotes a property called oxygen storage.

[0004] During lean operation, the converter stores oxygen. The stored oxygen is used during rich operation. CeO2 undergoes the following chemical reactions: During rich operation $2CeO_2 + CO \rightarrow CO_2 + Ce_2O_3$ and during lean operation $Ce_2O_3 + \frac{1}{2}O_2 \rightarrow 2CeO_2$. Oxygen storage

increases HC,CO and NOx conversion efficiency when the exhaust equivalence ratio (ϕ) moves rich or lean. In practice, transient engine operation cause rich and lean equivalence ratio ϕ errors.

[0005] The equivalence ratio ϕ is the fuel to air ratio observed divided by the stoichiometric fuel to air ratio. The stoichiometric value is the chemically correct mixture of fuel to air. At stoichiometry, substantially all of the carbon and hydrogen in the fuel are converted to CO_2 and H_2O. An equivalence ratio $\phi < 1$ is considered lean while an equivalence ratio $\phi > 1$ is considered rich. Traditional vehicle engines are designed to operate at stoichiometry ($\phi = 1$) since most regulated exhaust gases are either oxidized or reduced at stoichiometry.

[0006] Effectiveness of a catalytic converter is determined by measuring the conversion efficiency for HC, CO, and NOx. When a converter is new, conversion efficiency at an equivalence ratio $\phi = 1$ is high (99% or more) and the catalyst processes a larger range of equivalence ratio ϕ variations. When a catalytic converter has been used for an extended period, such as 100,000 miles of vehicle operation, the catalytic converter efficiency is reduced due to deterioration of the surface of the converter. Converter efficiency also declines as the equivalence ratio ϕ deviates from 1.

[0007] Automotive fuels include hydrogen and carbon compounds and a certain amount of sulfur, which is inherent to most crude oil. In the refining process, sulfur levels are reduced but are not completely eliminated from the fuel.

[0008] Sulfur is a well-known poison to catalyst performance. Sulfur interacts negatively with two distinctly different but equally important types of reactive sites in a modern automotive catalytic converter. Sulfur enters the catalyst as gas-phase SO_2. SO_2 can react with the precious metal sites (Pt, Pd or Rh) in the catalyst under rich conditions by reaction (1):

$$SO_2\,(g) + Pt\,(Pd, Rh) \rightarrow Pt\text{-}S \qquad (1) \qquad \text{[rich conditions]}$$

This reaction diminishes the effectiveness of Pt ,Pd or Rh for the removal of HC, CO and NOx from the exhaust. Alternatively, under lean conditions gas phase SO2 oxidizes via reaction (2):

$$SO2\ (g) + 1/2O2\ (g) \rightarrow SO3\ (g) \qquad (2) \qquad [\text{lean conditions}]$$

After the generation of gas phase SO3, that compound can react with CeO2 in the catalyst to poison the "oxygen storage sites", via reaction (3):

$$2\ SO3\ (g) + CeO2 \rightarrow Ce(SO4)2 \qquad (3) \qquad [\text{lean conditions}]$$

Reaction (3) reduces the effectiveness of the catalyst for the catalytic removal of CO and NOx from the exhaust.

SUMMARY OF THE INVENTION

[0009] A control method and apparatus has been developed which reduces the effects of sulfur on catalytic converter performance. The execution of a specific lean and rich equivalence ratio ϕ at a specific periodic rate encourages the following reactions. During a certain specific lean equivalence ratio ϕ, sulfur on precious metal sites is oxidized to SO2 via reaction (4):

$$Pt\text{-}S + O2\ (g) \rightarrow Pt + SO2\ (g) \qquad (4) \qquad [\text{lean conditions}]$$

This cleaning reaction restores the effectiveness of Pt, Pd, or Rh for the removal of HC, CO, and NOx from the exhaust. Certain specific rich operation can "clean" the oxygen storage sites by reaction (5):

$$Ce2O2(SO4) + CO \rightarrow Ce2O3 + SO2\ (g) + CO2\ (g) \quad (5) \quad [\text{rich conditions}].$$

[0010] Thus, with the right combination of rich and lean operation, we have the ability to keep both the precious metal sites (Pt, Pd, or Rh) and the CeO2 sites clean of sulfur. During the rich conditions, sulfur is preferentially removed from the CeO2 sites by reaction (5), and under lean conditions, sulfur is removed from the precious metal sites by reaction (4). The invention uses the cleaning reactions (4) and (5), which are faster than the poisoning reactions (1) and (3). Ultimately, the rates of poisoning reactions are controlled by the concentrations of sulfur in the fuel.

[0011] The present invention utilizes the equivalence ratio ϕ and periodically sweeps through both lean and rich conditions at a periodic frequency. The adverse effects of sulfur on the converter are reduced by encouraging the chemical reactions described in equations 4 and 5.

[0012] Through experimentation, calibration values have been found that enhance the performance of typical three-way catalytic converters.

[0013] The present invention preferably moves the equivalence ratio ϕ lean (ϕ = .924) for a half a second and then (rich (ϕ = 1.09) for a half a second. This sequence is preferably repeated once every four seconds, but any combination of equivalence ratio ϕ changes and time periods are considered within the scope of the present invention. These short equivalence ratio ϕ excursions are preferably executed during steady state or near steady state engine operating conditions where they have minimal effects on engine speed. The average efficiency of the converter for processing HC, CO, and NOx is vastly improved compared to traditional equivalence ratio ϕ control methods.

DESCRIPTION OF THE DRAWINGS

[0014] Figure 1 is a diagrammatic drawing of an engine control system including a catalytic converter;

[0015] Figure 2A is a flow chart of a preferred method of the present invention;

[0016] Figure 2B is a plot illustrating the preferred method of the present invention; and

[0017] Figure 3 is a plot illustrating the improved converter performance of the present invention.

DESCRIPTION OF AN EXEMPLARY EMBODIMENT

[0018] Figure 1 is a diagrammatic drawing of an engine control system 10 of the present invention. The engine control system 10 includes an internal combustion engine (ICE) 12 which may comprise a spark ignition engine or diesel engine, but is not limited to such. A powertrain controller 14 equipped with software, analog and digital inputs and outputs (I/O), and communication circuitry for operation with an automotive communication network, controls the ICE 12. The controller 14 receives engine sensor inputs such as inlet mass airflow, throttle position, manifold pressure, crankshaft position, engine exhaust oxygen, and coolant temperature, and processes a controlled output signal to engine fuel injectors and spark ignition. Various other standard engine signals may also be used in the control system 10, but are not shown in Figure 1.

[0019] The ICE 12 is further connected to an exhaust manifold 16 and a three-way catalytic converter 18. The catalytic converter 18 preferably comprises an Al2O3 monolithic walled substrate, which acts as a support, and a mixture of Pt, Pd, Rh, CeO2 and other elements, compounds, and rare earths are deposited onto the substrate to form a catalytic surface.

[0020] In one embodiment of the present invention, the fuel control system comprises an open loop (OL) control signal and a closed loop (CL) control signal, which are combined mathematically to generate the actual fuel control signal for control system 10. The OL signal is calculated by measuring air mass entering the ICE 12 and calculating a fuel amount that attempts to control the equivalence ratio ϕ to a value of 1, the ideal level for efficient catalytic converter operation. Because of component variation, it is

difficult to control the equivalence ratio ϕ to a precise value of 1. Because of imperfections in calculating OL equivalence ratio ϕ control, the present system 10 is equipped with an exhaust oxygen sensor (EOS) 10 that measures oxygen content. The EOS may be a discrete switch, or analog device, but is not limited to such, depending on the control algorithms and hardware of the controller 14. The switch type EOS is used to generate the plots shown in Figure 2B. The CL control system is formed by adjusting the equivalence ratio ϕ based on the EOS signal.

[0021] Figure 2A is a flow chart of a CL control method of the present invention. Starting at block 50, the method allows a wait time to pass before execution of the present method to allow the last calculated fuel corrections to propagate through the ICE 12 into the exhaust stream. At block 52, the old EOS state is saved in the memory of the controller 14. Block 54 determines if the present EOS value is greater than or equal to a setpoint indicative of an equivalence ratio ϕ of 1. If the EOS is not greater than the setpoint, then the equivalence ratio ϕ in the ICE 12 will be lean as shown at block 56. Block 58 determines if the present EOS state is different from the old EOS state. If the EOS states are not different, then the method at block 62 will add the closed loop fuel signal (CLFUEL) to a calibration value (CAL2) to move the equivalence ratio ϕ to a rich state. The term CAL2 is used to learn or integrate out system errors and is typically of a smaller magnitude than (CAL1). CAL2 preferably represents the amount of fuel that produces an equivalence ratio ϕ change of 0.003.

[0022] Returning to block 58, if the EOS states are different, then the method at block 60 will increment COUNTER1 and block 64 will determine if the COUNTER1 is greater than or equal to a calibration value (CAL4), representing the time between execution of the converter sulfur cleaning equivalence ratio ϕ change. A typical value for CAL4 is 4 seconds, but any time period is considered within the scope of the present invention. If the COUNTER1 is not greater than or equal to CAL4 or FLAG1 is not true,

then the method at block 66 will add to the closed loop fuel signal CLFUEL a calibration value CAL1 that preferably produces a 0.043 equivalence ratio ϕ change, but any equivalence ratio change is considered within the scope of the present invention. CAL1 is scaled to make the fuel system dither or oscillate from a rich to lean state and a lean to rich state. This control technique is used to overcome signal noise in the system 10. The preferable CAL1 values are from 0 to 0.04 equivalence ratio changes.

[0023] If the COUNTER1 is greater than CAL4 or FLAG1 is not true, then the method at block 68 will add the closed loop fuel signal CLFUEL to a calibration value (CAL3A). CAL 3A is used to move the equivalence ratio ϕ 0.09 in the rich direction. CAL3A is used for cleaning sulfur effects on converter oxygen storage sites. Block 70 determines if FLAG1 is true and if FLAG1 is true, then block 72 sets FLAG1 false.

[0024] Returning to block 54, if the EOS value is greater than or equal to the setpoint, then the EOS state at block 74 will be determined to be rich. Block 76 determines if the present EOS state is different from the old EOS state. If the EOS states are not different, then the method at block 78 will subtract from the closed loop fuel signal CLFUEL the calibration value (CAL2). CAL2 is used to remove rich system errors. If the EOS states are different, then the method at block 80 will subtract from the closed loop fuel CLFUEL the calibration value (CAL1), which is used to make the system dither or oscillate to overcome system noise.

[0025] Block 82 determines if the COUNTER1 is greater than or equal to the calibration value (CAL4). If the COUNTER1 is not greater than or equal to CAL4, the method returns to the beginning. If the COUNTER1 is greater than or equal to CAL4, then the method at block 84 will subtract from the closed loop fuel signal CLFUEL the calibration value (CAL3B), which is used to generate a lean equivalence ratio ϕ change of 0.076 to clean sulfur off the converters Pt, Pd, and Rh metals. FLAG1 is set to true at block 86 and the counter is reset at block 88. The use of FLAG1 allows a

symmetrical return of the system from sulfur cleaning to non-sulfur cleaning operation.

[0026] Figure 2B illustrates the operation of the present invention and Figure 3 illustrates the improved converter performance of the present invention. Plot 100 is the equivalence ratio ϕ setpoint and plot 102 illustrates the oscillation between a rich and lean states. As can be seen in Figure 2B, CAL1 (104) forces the system to dither or oscillate. CAL3A (106) and CAL3B (108) are the sulfur cleaning equivalence ratio ϕ signals. Preferable values of CAL 3A and CAL 3B are 0.09 and 0.076 equivalence ratio ϕ change, respectively; however, rich or lean sulfur cleaning equivalence ratio ϕ values may be different. CAL2 (110) is a typical system error learning equivalence ratio ϕ signal.

[0027] While this invention has been described in terms of some specific embodiments, it will be appreciated that other forms can readily be adapted by one skilled in the art. Accordingly, the scope of this invention is to be considered limited only by the following claims.